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A CRITICAL EVALUATION OF TWO-EQUATION MODELS FOR NEAR WALL TURBULENCE

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ABSTRACT

A variety of two-equation turbulence models - including several versions of the $K - \epsilon$ model as well as the $K - \omega$ model - are analyzed critically for near wall turbulent flows from a theoretical and computational standpoint. It is shown that the $K - \epsilon$ model has two major problems associated with it: the lack of natural boundary conditions for the dissipation rate and the appearance of higher-order correlations in the balance of terms for the dissipation rate at the wall. In so far as the former problem is concerned, either physically inconsistent boundary conditions have been used or the boundary conditions for the dissipation rate have been tied to higher-order derivatives of the turbulent kinetic energy which leads to numerical stiffness. The $K - \omega$ model can alleviate these problems since the asymptotic behavior of ω is known in more detail and since its near wall balance involves only exact viscous terms. However, the modeled form of the ω equation that is used in the literature is incomplete - an exact viscous term is missing which causes the model to behave in an asymptotically inconsistent manner. By including this viscous term - and by introducing new wall damping functions with improved asymptotic behavior - a new $K - \tau$ model (where $\tau \equiv 1/\omega$ is turbulent time scale) is developed. It is demonstrated that this new model is computationally robust and yields improved predictions for turbulent boundary layers.

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1. INTRODUCTION

An increasing number of practical engineering calculations of turbulent flows have been based on two-equation turbulence models. For many technologically important turbulent flows, two-equation models represent a nice compromise between zero or one equation models and second-order closures (the former models tend to require too many ad hoc empiricisms whereas second-order closure models can be overly expensive for design calculations). The $K - \epsilon$ model [1] is the most popular two-equation turbulence model in use today. When utilized in conjunction with wall functions, the $K - \epsilon$ model is reasonably well-behaved and has been applied to the solution of a variety of engineering problems with a moderate amount of success. However, many important technological applications require the integration of turbulence models directly to a solid boundary, particularly in problems where wall transport properties are needed or where there is flow separation. The problem of developing low-Reynolds-number near wall corrections to the $K - \epsilon$ model that can be robustly and accurately integrated to a solid boundary remains unresolved so that models along alternative lines continue to be proposed (see Patel, Rodi, and Scheuerer [2] for a recent review). Most of these near wall $K - \epsilon$ models involve an excessive amount of ad hoc empiricisms and are numerically stiff in turbulent boundary layer flows. This motivated some researchers to pursue alternative two-equation models based on a modeled transport equation for the turbulent time scale. The most notable example is the $K - \omega$ model of Wilcox and co-workers [3, 4] where modeled transport equations for the turbulent kinetic energy K and reciprocal turbulent time scale ω are solved. There is considerable evidence that the $K - \omega$ model is more computationally robust than the $K - \epsilon$ model for the integration of turbulent flows to a solid boundary. However, the $K - \omega$ model yields solutions for the turbulent kinetic energy that are asymptotically inconsistent near a solid boundary [4]. Hence, there is the need to re-examine this problem from a basic theoretical and computational standpoint. This establishes the motivation for the present paper.

In this paper, the near-wall asymptotics of two-equation turbulence models will be examined from a basic theoretical standpoint. It will be shown that the $K - \epsilon$ model has two major problems associated with it. The first arises from the lack of natural boundary conditions for the turbulent dissipation rate which has caused modelers to use a variety of derived boundary conditions that are either asymptotically inconsistent (e.g., the boundary condition of vanishing normal derivative of dissipation) or numerically stiff (e.g., the boundary condition that ties the dissipation to higher-order derivatives of the turbulent kinetic energy). The second problem – which can be the source of substantial inaccuracies and numerical stiffness – is tied to the fact that the balance of terms at the wall in the modeled dissipation rate transport equation depends on higher-order correlations whose models have

considerable uncertainties.

It will be demonstrated that both of these problems can be largely alleviated by solving a modeled transport equation for the turbulent time scale $\tau \equiv K/\varepsilon$ since: (a) near the wall, $\tau \sim y^2/2\nu$ which provides the needed natural boundary conditions, and (b) the balance of terms at the wall in the modeled transport equation for τ involves only *exact* viscous terms. It will be argued that these features are primarily responsible for the more computationally robust performance of the $K - \omega$ model of Wilcox and co-workers [3, 4]. However, the $K - \omega$ model yields results for the turbulent kinetic energy – as well as other turbulence quantities – that are asymptotically inconsistent (e.g., near the wall, $K \sim y^{3.23}$ instead of the expected $K \sim y^2$ behavior). It will be proven that this problem arises due to the fact that an exact viscous cross-diffusion term is missing in the modeled ω -transport equation. A new $K - \tau$ model is obtained by including this exact viscous term and by substituting improved wall damping functions which are obtained by an asymptotic analysis using the results of direct numerical simulations of turbulent channel flow (Mansour, Kim, and Moin [5]). The new model will be tested for the flat plate turbulent boundary layer and comparisons will be made with the predictions of other models (i.e., the $K - \varepsilon$ models of Launder and Sharma [6] and Chien [7] as well as the $K - \omega$ model [4]) in order to assess its performance.

2. NEAR WALL ASYMPTOTIC ANALYSIS

For simplicity, we will restrict our analysis to incompressible turbulent flows (however, the crucial conclusions that will be drawn carry over to compressible flows). The mean velocity \bar{u} and mean pressure \bar{p} are solutions of the Reynolds averaged Navier-Stokes and continuity equations given by

$$\frac{\partial \bar{u}_i}{\partial t} + \bar{u}_j \frac{\partial \bar{u}_i}{\partial x_j} = -\frac{\partial \bar{p}}{\partial x_i} + \nu \nabla^2 \bar{u}_i + \frac{\partial \tau_{ij}}{\partial x_j} \quad (1)$$

$$\frac{\partial \bar{u}_i}{\partial x_i} = 0 \quad (2)$$

where $\tau_{ij} = -\overline{u'_i u'_j}$ is the Reynolds stress tensor, ν is the kinematic viscosity, and the usual Einstein summation convention applies to repeated indices. We will consider the commonly used two-equation models based on an eddy viscosity where

$$\tau_{ij} = -\frac{2}{3} K \delta_{ij} + \nu_T \left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \right) \quad (3)$$

and

$$\nu_T = C_\mu \frac{K^2}{\varepsilon} \quad (4)$$

given that $K \equiv \frac{1}{2} \overline{u'_i u'_i}$ is the turbulent kinetic energy, $\varepsilon = \nu \overline{\partial u'_i / \partial x_j \partial u'_i / \partial x_j}$ is the turbulent dissipation rate, and C_μ is a dimensionless constant at high turbulence Reynolds numbers. In two-equation models, transport equations are solved for any two linearly independent variables constructed from K and ε . In the $K - \varepsilon$ model, modeled transport equations for K and ε are solved; in the $K - \omega$ model, modeled transport equations for K and the reciprocal turbulent time scale $\omega \equiv \varepsilon/K$ are solved; and in the $K - \tau$ model, modeled transport equations for K and the turbulent time scale $\tau \equiv K/\varepsilon$ are solved. The exact transport equations for K and ε are as follows [8]:

$$\frac{DK}{Dt} = \tau_{ij} \frac{\partial \bar{u}_i}{\partial x_j} - \varepsilon - \mathcal{D} + \nu \nabla^2 K \quad (5)$$

$$\frac{D\varepsilon}{Dt} = \mathcal{P}_\varepsilon - \Phi_\varepsilon - \mathcal{D}_\varepsilon + \nu \nabla^2 \varepsilon \quad (6)$$

where $D/Dt = \partial/\partial t + \bar{\mathbf{u}} \cdot \nabla$. In (5) - (6),

$$\mathcal{D} = \frac{\partial}{\partial x_i} \left(\frac{1}{2} \overline{u'_j u'_j u'_i} + \overline{p' u'_i} \right) \quad (7)$$

$$\mathcal{D}_\varepsilon = 2\nu \frac{\partial}{\partial x_i} \left(\frac{\partial p'}{\partial x_j} \frac{\partial u'_i}{\partial x_j} \right) + \nu \frac{\partial}{\partial x_j} \left(u'_j \frac{\partial u'_i}{\partial x_k} \frac{\partial u'_i}{\partial x_k} \right) \quad (8)$$

are turbulent transport terms, and

$$\mathcal{P}_\varepsilon = -2\nu \frac{\partial u'_i}{\partial x_j} \frac{\partial u'_k}{\partial x_j} \frac{\partial \bar{u}_i}{\partial x_k} - 2\nu \frac{\partial u'_j}{\partial x_i} \frac{\partial u'_j}{\partial x_k} \frac{\partial \bar{u}_i}{\partial x_k} - 2\nu \frac{\partial u'_i}{\partial x_k} \frac{\partial u'_i}{\partial x_j} \frac{\partial \bar{u}_k}{\partial x_j} - 2\nu u'_k \frac{\partial u'_i}{\partial x_j} \frac{\partial^2 \bar{u}_i}{\partial x_j \partial x_k} \quad (9)$$

$$\Phi_\varepsilon = 2\nu^2 \frac{\partial^2 u'_i}{\partial x_j \partial x_k} \frac{\partial^2 u'_i}{\partial x_j \partial x_k} \quad (10)$$

are, respectively, the production and destruction of dissipation terms.

The Taylor series expansions for the components of $\mathbf{u}'_i \equiv (u', v', w')$ are as follows near a wall:

$$u' = a_1 y + a_2 y^2 + \dots \quad (11)$$

$$v' = b_2 y^2 + b_3 y^3 + \dots \quad (12)$$

$$w' = c_1 y + c_2 y^2 + \dots \quad (13)$$

where $a_i = a_i(x, z, t)$, $b_i = b_i(x, z, t)$ and $c_i = c_i(x, z, t)$ given that the coordinate y is normal to the wall (later, wall coordinates will be used where $y^+ = y u_\tau / \nu$ given that u_τ is the shear velocity). Of course, the no slip condition at the wall eliminates a_0 , b_0 , and c_0 whereas the continuity equation eliminates b_1 (c.f., Hinze [8]). It is a straightforward matter to show that near a wall

$$K = \mathcal{O}(y^2), \quad \varepsilon = \mathcal{O}(1), \quad \tau = \mathcal{O}(y^2) \quad (14)$$

$$\frac{\partial \bar{u}}{\partial y} = \mathcal{O}(1), \quad \overline{u'^2} = \mathcal{O}(y^2), \quad \overline{u'v'} = \mathcal{O}(y^3) \quad (15)$$

$$\overline{v'^2} = \mathcal{O}(y^4), \quad \overline{w'^2} = \mathcal{O}(y^2), \quad \mathcal{P} = \mathcal{O}(y^3) \quad (16)$$

$$\mathcal{D} = \mathcal{O}(y), \quad \mathcal{P}_\epsilon = \mathcal{O}(y), \quad \Phi_\epsilon = \mathcal{O}(1) \quad (17)$$

$$\mathcal{D}_\epsilon = \mathcal{O}(1), \quad \nabla^2 K = \mathcal{O}(1), \quad \nabla^2 \epsilon = \mathcal{O}(1) \quad (18)$$

where $\mathcal{P} \equiv \tau_{ij} \partial \bar{u}_i / \partial x_j$ is the turbulence production.

An asymptotic analysis of the $K - \epsilon$ model will be conducted first. In the $K - \epsilon$ model, the eddy viscosity near a wall is taken to be of the form

$$\nu_T = C_\mu f_\mu \frac{K^2}{\epsilon}. \quad (19)$$

The asymptotic analysis presented in this section indicates that $f_\mu = \mathcal{O}(1/y)$ near the wall since, due to (15), ν_T must be of $\mathcal{O}(y^3)$ in this region. Of course, sufficiently far from the wall f_μ assumes a value of 1. (C_μ is a constant which is typically taken to be 0.09). The turbulent transport term \mathcal{D} in the kinetic energy equation (5) is modeled using a gradient transport hypothesis:

$$\mathcal{D} = - \frac{\partial}{\partial x_i} \left(\frac{\nu_T}{\sigma_K} \frac{\partial K}{\partial x_i} \right) \quad (20)$$

where σ_K is a constant. From (14), (17), and (19), it is clear that this model is *not* asymptotically consistent. However, \mathcal{D} consists of two parts – the triple velocity term and the pressure diffusion term – as given by (7). Direct numerical simulations of the Navier-Stokes equations indicate that

$$\frac{\partial}{\partial x_i} (\overline{pu'_i}) \ll \frac{\partial}{\partial x_i} \left(\frac{1}{2} \overline{u'_i u'_j u'_i} \right)$$

except very close to the wall (i.e., inside of $y^+ = 2$; see Mansour, Kim, and Moin [5]) and in this region \mathcal{D} is negligible in comparison to the dissipation rate and the viscous diffusion of the turbulent kinetic energy. Hence, if we approximate \mathcal{D} by

$$\mathcal{D} \doteq \frac{\partial}{\partial x_i} \left(\frac{1}{2} \overline{u'_i u'_j u'_i} \right) \quad (21)$$

then the gradient transport model (20) is asymptotically consistent since the right-hand-side of (20) and (21) are both of $\mathcal{O}(y^3)$ as the wall is approached. Hence, it would appear that the asymptotic errors introduced by the use of (20) in the $K - \epsilon$ model are probably not that significant.

The turbulent transport term \mathcal{D}_ϵ in the dissipation rate transport equation is also modeled by a gradient transport hypothesis:

$$\mathcal{D}_\epsilon = - \frac{\partial}{\partial x_i} \left(\frac{\nu_T}{\sigma_\epsilon} \frac{\partial \epsilon}{\partial x_i} \right) \quad (22)$$

(where σ_ϵ is a constant) in the $K - \epsilon$ model. This model is not asymptotically consistent since $\mathcal{D}_\epsilon = \mathcal{O}(1)$ near a wall while the right-hand-side of (21) is $\mathcal{O}(y^2)$. However, this inconsistency is probably not of great consequence since both \mathcal{D}_ϵ and Φ_ϵ are of $\mathcal{O}(1)$ near a wall but direct numerical simulations of turbulent channel flow indicate that $\mathcal{D}_\epsilon \ll \phi_\epsilon$ (c.f. Mansour, Kim, and Moin [5]).

The production of dissipation \mathcal{P}_ϵ and the destruction of dissipation Φ_ϵ are modeled as follows

$$\mathcal{P}_\epsilon = C_{\epsilon 1} f_1 \frac{\epsilon}{K} \tau_{ij} \frac{\partial \bar{u}_i}{\partial x_j} \quad (23)$$

$$\Phi_\epsilon = C_{\epsilon 2} f_2 \frac{\epsilon^2}{K} \quad (24)$$

in the $K - \epsilon$ model where the wall damping functions $f_1, f_2 \rightarrow 1$ away from the wall. It is clear from (14) - (17) that these models are asymptotically consistent if $f_1 = \mathcal{O}(1)$ and $f_2 = \mathcal{O}(y^2)$ near a wall. *It thus follows that the $K - \epsilon$ model will generate solutions for K, ϵ and $\overline{u'v'}$ that are asymptotically consistent if the damping functions $f_\mu = \mathcal{O}(1/y)$ and $f_2 = \mathcal{O}(y^2)$ near a wall with $f_1 = 1$.*

While the $K - \epsilon$ model can be made asymptotically consistent in near wall turbulent flows by the introduction of only two wall damping functions - namely, $f_\mu = \mathcal{O}(1/y)$ and $f_2 = \mathcal{O}(y^2)$ - there are still some other major problems that need to be discussed. There are no natural boundary conditions on ϵ ; consequently, boundary conditions must be either derived or postulated. One of the commonly used derived boundary conditions is

$$\nu \frac{\partial^2 K}{\partial y^2} = \epsilon \quad (25)$$

at the wall which is a rigorous consequence of the exact transport equation for K . Equation (25) requires information at the wall on the second-order derivative of the turbulent kinetic energy - a feature that can lead to considerable numerical stiffness [2]. Some of the stiffness can be alleviated by utilizing the alternative version of (25):

$$2\nu \left(\frac{\partial \sqrt{K}}{\partial y} \right)^2 = \epsilon \quad (26)$$

at the wall. However, even (26) can give rise to considerable numerical problems. The Neumann boundary condition

$$\frac{\partial \epsilon}{\partial y} = 0 \quad (27)$$

has been used in a variety of applications of the $K - \epsilon$ model (c.f. Lam and Bremhorst [9]). Although (27) is more computationally robust, it is completely *ad hoc* with no solid

theoretical or experimental justification. In fact, recent direct numerical simulations of the Navier-Stokes equations for turbulent channel flow indicate that [5]

$$\frac{1}{\epsilon^+} \frac{\partial \epsilon^+}{\partial y^+} \doteq -0.25$$

at the wall; under such circumstances the use of (27) could lead to substantial errors.

The other major problem with the dissipation rate transport equation lies in the balance of terms at the wall. At a solid boundary, (6) reduces to

$$\nu \frac{\partial^2 \epsilon}{\partial y^2} = \Phi_\epsilon + \mathcal{D}_\epsilon + \frac{\partial \epsilon}{\partial t} \quad (28)$$

For a fully-developed turbulent boundary layer, $\partial \epsilon / \partial t = 0$ and $\mathcal{D}_\epsilon \ll \Phi_\epsilon$ as discussed earlier; hence, (28) simplifies to

$$\nu \frac{\partial^2 \epsilon}{\partial y^2} = \Phi_\epsilon. \quad (29)$$

Both (28) and (29) have a major deficiency: the balance of terms at the wall involves higher-order correlations. This puts significant pressure on the accuracy of the near wall modeling of the destruction of dissipation term that can further exasperate the numerical stiffness problem.

On the other hand, the turbulent time scale $\tau \equiv K/\epsilon$, has a variety of natural boundary conditions. It is a simple matter to show that close to a wall

$$\tau \doteq \frac{y^2}{2\nu} \quad (30)$$

and, hence, at the wall

$$\tau = \frac{d\tau}{dy} = 0, \quad \frac{d^2\tau}{dy^2} = \frac{1}{\nu}. \quad (31)$$

Equations (30) - (31) have the advantage of being valid for *any* near wall turbulence where the fluctuating velocity is expandable in a Taylor series. Furthermore, the balance at the wall in the transport equation for τ only involves *exact* viscous terms. This can be seen directly from the exact τ -transport equation which takes the form

$$\begin{aligned} \frac{D\tau}{Dt} = & \frac{\tau}{K} \tau_{ij} \frac{\partial \bar{u}_i}{\partial x_j} - 1 - \frac{\tau}{K} \mathcal{D} - \frac{\tau^2}{K} \mathcal{P}_\epsilon + \frac{\tau^2}{K} \Phi_\epsilon + \frac{\tau^2}{K} \mathcal{D}_\epsilon \\ & + \frac{2\nu}{K} \frac{\partial K}{\partial x_i} \frac{\partial \tau}{\partial x_i} - \frac{2\nu}{\tau} \frac{\partial \tau}{\partial x_i} \frac{\partial \tau}{\partial x_i} + \nu \nabla^2 \tau \end{aligned} \quad (32)$$

and, hence, at the wall $y = 0$, the leading terms are

$$\frac{2\nu}{K} \frac{\partial K}{\partial y} \frac{\partial \tau}{\partial y} - \frac{2\nu}{\tau} \frac{\partial \tau}{\partial y} \frac{\partial \tau}{\partial y} + \nu \frac{\partial^2 \tau}{\partial y^2} - 1 = 0. \quad (33)$$

Here, each term on the left-hand-side of (33) is $\mathcal{O}(1)$. The balance of terms in (33) is guaranteed if $\tau \doteq y^2/2\nu$ near the wall. It therefore appears that the two major problems with the $K - \varepsilon$ model – namely, the lack of natural boundary conditions for ε and the appearance of higher-order correlations in the balance of terms at the wall – can be overcome by the use of a $K - \tau$ model.

While the development of a two-equation turbulence model based on the turbulent time scale has been discussed in the literature (c.f. Reynolds [10] and Bardina [11]), no systematic study of such models has been conducted for near wall turbulence. Only the $K - \omega$ model – which is based on a modeled transport equation for the reciprocal turbulent time scale $\omega \equiv 1/\tau$ – has been studied in these flows to any extent (see Wilcox and Traci [3] and Wilcox [4]). In the $K - \omega$ model, a modeled transport equation for the reciprocal time scale ω is solved which is of the form [4]

$$\frac{D\omega}{Dt} = C_{\omega 1} \frac{\omega}{K} \tau_{ij} \frac{\partial \bar{u}_i}{\partial x_j} - C_{\omega 2} \omega^2 + \frac{\partial}{\partial x_i} \left[\left(\nu + \frac{\nu_T}{\sigma_\omega} \right) \frac{\partial \omega}{\partial x_i} \right] \quad (34)$$

where $\nu_T = C_\mu K/\omega$ and $C_{\omega 1}, C_{\omega 2}$ and σ_ω are constants which assume the values of 5/9, 5/6, and 2, respectively (again, $C_\mu = 0.09$). However, we will now show that (34) is inconsistent with the exact transport equation for ω near a wall: an exact viscous term is missing and $C_{\omega 2}$ must be damped. The exact transport equation for ω takes the form

$$\frac{D\omega}{Dt} = \frac{\mathcal{P}_\varepsilon}{K} - \frac{\Phi_\varepsilon}{K} - \frac{\mathcal{D}_\varepsilon}{K} - \frac{\omega \mathcal{P}}{K} + \omega^2 + \frac{\omega \mathcal{D}}{K} + \frac{2\nu}{K} \frac{\partial \omega}{\partial x_i} \frac{\partial K}{\partial x_i} + \nu \nabla^2 \omega. \quad (35)$$

Hence, it is clear that an exact viscous cross-diffusion term – given by $(2\nu/K)\partial\omega/\partial x_i \partial K/\partial x_i$ in (35) – is missing in the modeled ω -transport equation of Wilcox and co-workers. From (35), it is a simple matter to show that the leading terms in the near wall balance of ω are as follows:

$$\frac{2\nu}{K} \frac{\partial \omega}{\partial y} \frac{\partial K}{\partial y} + \nu \frac{\partial^2 \omega}{\partial y^2} + \omega^2 \doteq 0 \quad (36)$$

at the plane solid boundary $y = 0$. Equation (36) is consistent with asymptotic solutions for K and ω that behave correctly near the wall, i.e.,

$$K \doteq \alpha y^2, \quad \omega \doteq \frac{2\nu}{y^2}. \quad (37)$$

In stark contrast to (36), the $K - \omega$ model of Wilcox based on (34) yields the balance of terms

$$\nu \frac{\partial^2 \omega}{\partial y^2} - C_{\omega 2} \omega^2 = 0 \quad (38)$$

at the wall, which is incompatible with (37). Hence, the $K - \omega$ model of Wilcox yields asymptotically inconsistent solutions in near wall turbulence (e.g., $K \sim y^{3.23}$; see Wilcox [4]).

The $K - \omega$ model can be made asymptotically consistent by the addition of the viscous cross-diffusion term

$$\frac{2\nu}{K} \frac{\partial \omega}{\partial x_i} \frac{\partial K}{\partial x_i}$$

and by decomposition of $C_{\omega 2}$ as follows

$$C_{\omega 2} = C'_{\omega 2} - 1 \quad (39)$$

where $C'_{\omega 2}$ must be damped of $\mathcal{O}(y^2)$ near the wall. However, we feel that it is preferable to derive a modeled transport equation for $\tau \equiv 1/\omega$ since τ is *not* singular near the wall. A new $K - \tau$ model will be derived in the next section which is asymptotically consistent.

3. A NEW $K - \tau$ MODEL

The exact transport equation for the turbulent time scale τ takes the form

$$\frac{D\tau}{Dt} = \frac{\tau}{K} \mathcal{P} - 1 - \frac{\tau}{K} \mathcal{D} - \frac{\tau^2}{K} \mathcal{P}_e + \frac{\tau^2}{K} \Phi_e + \frac{\tau^2}{K} \mathcal{D}_e + \frac{2\nu}{K} \frac{\partial K}{\partial x_i} \frac{\partial \tau}{\partial x_i} - \frac{2\nu}{\tau} \frac{\partial \tau}{\partial x_i} \frac{\partial \tau}{\partial x_i} + \nu \nabla^2 \tau \quad (40)$$

which is obtained from a straightforward combination of (5) and (6). Models for \mathcal{P}_e , Φ_e , \mathcal{D}_e and \mathcal{D} are needed for closure. The production of dissipation term will be modeled as it is in the $K - \varepsilon$ model, i.e.,

$$\mathcal{P}_e = C_{e1} \frac{\varepsilon}{K} \tau_{ij} \frac{\partial \bar{u}_i}{\partial x_j} \equiv \frac{C_{e1}}{\tau} \tau_{ij} \frac{\partial \bar{u}_i}{\partial x_j} \quad (41)$$

where $C_{e1} = 1.44$. As mentioned earlier, this model is asymptotically consistent. The destruction of dissipation term, Φ_e will also be modeled similarly, i.e.,

$$\Phi_e = C_{e2} f_2 \frac{\varepsilon^2}{K} \equiv C_{e2} f_2 \frac{K}{\tau^2}. \quad (42)$$

Here, asymptotic consistency with (17) requires that f_2 be damped of $\mathcal{O}(y^2)$ near a wall. We will use a variation of the form for C_{e2} suggested by Hanjalic and Launder [12]:

$$C_{e2} = 1.83 \left[1 - \frac{2}{9} \exp(-Re_t/6)^2 \right] \quad (43)$$

where $Re_t = K^2/\nu\varepsilon$ is the turbulence Reynolds number. Here, we set the high turbulence Reynolds number value of $C_{e2} = 1.83$ since it yields a somewhat more accurate value for the decay rate of grid turbulence than the traditional value of 1.92 (c.f. Reynolds [10]). An exponential form is chosen for the wall damping function f_2 as follows

$$f_2 = [1 - \exp(-y^+/A_2)]^2 \quad (44)$$

which is $\mathcal{O}(y^2)$ near the wall. Since at the wall

$$\frac{\partial^2 \epsilon^+}{\partial y^{+2}} = C_{\epsilon 2} f_2 \frac{\epsilon^{+2}}{K^+}. \quad (45)$$

A_2 can be evaluated if $\partial^2 \epsilon^+ / \partial y^{+2}$, ϵ^+ and K^+ are known. By using the wall values of these quantities from direct numerical simulations of turbulent channel flow [5] we obtain

$$A_2 \doteq 4.9.$$

The resulting model for Φ_ϵ is quite similar to that proposed recently by Myong and Kasagi [13].

The turbulent diffusion term for τ is defined by

$$\mathcal{D}_\tau = \frac{\tau^2}{K} \mathcal{D}_\epsilon - \frac{\tau}{K} \mathcal{D}. \quad (46)$$

This term will be modeled by the gradient transport hypothesis

$$\mathcal{D}_\tau = \frac{2\nu_T}{K\sigma_{\tau 1}} \frac{\partial K}{\partial x_i} \frac{\partial \tau}{\partial x_i} - \frac{2\nu_T}{\tau\sigma_{\tau 2}} \frac{\partial \tau}{\partial x_i} \frac{\partial \tau}{\partial x_i} + \frac{\partial}{\partial x_i} \left(\frac{\nu_T}{\sigma_{\tau 2}} \frac{\partial \tau}{\partial x_i} \right) \quad (47)$$

where ν_T is eddy viscosity and $\sigma_{\tau 1}$ and $\sigma_{\tau 2}$ are turbulent Prandtl numbers. In deriving (47) it has been assumed that the turbulent transport processes parallel the molecular ones (i.e., each turbulent transport term is coupled with a molecular diffusion term of the same general form). The turbulent Prandtl numbers for the last two terms on the right-hand-side of (47) are taken to be equal so that this pairing of molecular and turbulent diffusion terms is also true if the reciprocal time scale ω is chosen as a variable instead of τ (the choice of ω as a variable instead of τ should not alter the basic physics of the model). Of course, the eddy viscosity is taken to be of the form

$$\nu_T = C_\mu f_\mu K \tau \quad (48)$$

where $C_\mu = 0.09$ and f_μ is a wall damping function which is $\mathcal{O}(1/y)$ near the wall. By an analysis of the two distinct effects of low turbulence Reynolds number and near wall proximity, Myong and Kasagi [13] proposed the model

$$f_\mu = (1 + 3.45/\sqrt{Re_t})[1 - \exp(-y^+/70)]. \quad (49)$$

This model fits the experimental data [2] reasonably well with one exception – it is asymptotes to one somewhat too slowly. Hence, we will consider the alternative model

$$f_\mu = (1 + 3.45/\sqrt{Re_t}) \tanh(y^+/70) \quad (50)$$

since the hyperbolic tangent asymptotes to one faster by the necessary amount.

Now, for the purposes of clarity, we will summarize the $K - \tau$ model derived in this section:

$$\tau_{ij} = -\frac{2}{3}K\delta_{ij} + \nu_T \left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \right) \quad (51)$$

$$\nu_T = C_\mu f_\mu K \tau \quad (52)$$

$$\frac{DK}{Dt} = \tau_{ij} \frac{\partial \bar{u}_i}{\partial x_j} - \frac{K}{\tau} + \frac{\partial}{\partial x_i} \left[\left(\nu + \frac{\nu_T}{\sigma_K} \right) \frac{\partial K}{\partial x_i} \right] \quad (53)$$

$$\begin{aligned} \frac{D\tau}{Dt} = & (1 - C_{\epsilon 1}) \frac{\tau}{K} \tau_{ij} \frac{\partial \bar{u}_i}{\partial x_j} + (C_{\epsilon 2} f_2 - 1) + \frac{2}{K} \left(\nu + \frac{\nu_T}{\sigma_{\tau 1}} \right) \frac{\partial K}{\partial x_i} \frac{\partial \tau}{\partial x_i} \\ & - \frac{2}{\tau} \left(\nu + \frac{\nu_T}{\sigma_{\tau 2}} \right) \frac{\partial \tau}{\partial x_i} \frac{\partial \tau}{\partial x_i} + \frac{\partial}{\partial x_i} \left[\left(\nu + \frac{\nu_T}{\sigma_{\tau 2}} \right) \frac{\partial \tau}{\partial x_i} \right]. \end{aligned} \quad (54)$$

In (51) - (54), $C_\mu = 0.09$, $C_{\epsilon 1} = 1.44$, while $C_{\epsilon 2}$, f_μ , and f_2 are given by (43), (44) and (50), respectively. However, to complete the model, values for the turbulent Prandtl numbers $\sigma_{\tau 1}$, $\sigma_{\tau 2}$, and σ_K must be provided. In this regard, we first note that if

$$\sigma_{\tau 1} = \sigma_{\tau 2} = \sigma_K = \sigma_\epsilon$$

then the modeled τ -transport equation (54) is equivalent the ϵ transport equation

$$\frac{D\epsilon}{Dt} = C_{\epsilon 1} \frac{\epsilon}{K} \tau_{ij} \frac{\partial \bar{u}_i}{\partial x_j} - C_{\epsilon 2} f_2 \frac{\epsilon^2}{K} + \frac{\partial}{\partial x_i} \left[\left(\nu + \frac{\nu_T}{\sigma_\epsilon} \right) \frac{\partial \epsilon}{\partial x_i} \right]. \quad (55)$$

Since the standard ϵ -transport equation (55) is known to perform well in several high-Reynolds-number turbulent flows, it is reasonable to believe that $\sigma_{\tau 1}$, $\sigma_{\tau 2}$, σ_K and σ_ϵ must assume values that are reasonably close to one another. Furthermore, for local equilibrium flows with zero pressure gradient and logarithmic velocity profile, we must have [2]

$$C_{\epsilon 1} = C_{\epsilon 2} - (\kappa^2 / \sigma_\epsilon \sqrt{C_\mu}) \quad (56)$$

where $\kappa \doteq 0.4$ is the Von Karman constant. Hence, for the values of $C_{\epsilon 1}$, $C_{\epsilon 2}$ and C_μ chosen herein, it follows that

$$\sigma_\epsilon \doteq 1.36$$

and, hence,

$$\sigma_{\tau 1} \doteq \sigma_{\tau 2} \doteq \sigma_K \doteq 1.36. \quad (57)$$

It should be noted that the new modeled transport equation for τ given by (54) is equivalent to the ω -transport equation

$$\begin{aligned} \frac{D\omega}{Dt} = & (C_{\epsilon 1} - 1) \frac{\omega}{K} \tau_{ij} \frac{\partial u_i}{\partial x_j} - (C_{\epsilon 2} f_2 - 1) \omega^2 \\ & + 2 \left(\nu + \frac{\nu_T}{\sigma_{\tau 1}} \right) \frac{1}{K} \frac{\partial K}{\partial x_i} \frac{\partial \omega}{\partial x_i} + \frac{\partial}{\partial x_i} \left[\left(\nu + \frac{\nu_T}{\sigma_{\tau 2}} \right) \frac{\partial \omega}{\partial x_i} \right] \end{aligned} \quad (58)$$

which differs from that of Wilcox and co-workers by the presence of a cross diffusion term and by the damping of the coefficient of ω^2 to one at the wall.

Calculations will be presented in the next section using the common value of 1.36 for $\sigma_{\tau 1}$, $\sigma_{\tau 2}$ and σ_K which seems to be adequate for the present study. However, future research is needed to optimize these constants over a range of benchmark turbulent flows.

4. COMPARISON OF THE MODELS

Now, the performance of this new $K - \tau$ model will be examined for the flat plate turbulent boundary layer at zero pressure gradient. Comparisons will be made initially with the $K - \omega$ model of Wilcox [4] and the $K - \epsilon$ model of Launder and Sharma [6] (a comparison with the $K - \epsilon$ model of Chien [7] will be made later). The calculations to be presented were done with a two-dimensional boundary layer code based on the implicit marching scheme of Edwards et al. [14]. In the fully developed turbulent regime, approximately 100 grid points were used in the direction normal to the wall with the first grid point at $y^+ \doteq 0.2$. The profiles of the turbulent fields to be discussed in the figures are for a Reynolds number $Re_\theta \approx 16,000$ based on the momentum thickness (this will allow for comparisons with the experimental data described by Patel, Rodi, and Scheuerer [2] which was compiled from a variety of sources including Coles [15] and Schubauer [16]).

In Figure 1, the predictions of the $K - \tau$, $K - \omega$, and $K - \epsilon$ model for the mean velocity are compared with experimental data [2]. It is clear that each model yields a logarithmic velocity profile for $30 < y^+ < 300$ that is well within the range of the experimental data. Furthermore, each model correctly yields $u^+ = y^+$ close to wall (i.e., for $y^+ < 5$) and predicts the deviations from the law of the wall for $y^+ > 1000$. In Figure 2, the Reynolds shear stress predicted by these three models is shown. The predictions of the various models are extremely close for $y^+ > 10$. However, for $y^+ < 10$ the differences between the model predictions are significant. Among these models, only the $K - \tau$ model yields a profile where $\overline{u'v'} \sim y^3$ for $y^+ < 10$ as indicated by experiments; see Figure 3 and Patel et al. [2]. In Figure 4, the predictions of the $K - \tau$, $K - \omega$, and $K - \epsilon$ models for the turbulent kinetic energy are compared. The $K - \tau$ model yields a peak in K^+ of approximately 4 which is well

within the range of the experimental data [2] and the results of direct numerical simulations for turbulent channel flow [5]. On the other hand, the $K - \omega$ model – as well as the $K - \epsilon$ model of Launder and Sharma – appear to yield peaks in the turbulent kinetic energy that are rather low. The turbulent kinetic energy near the wall is shown on a logarithmic plot in Figure 5. Only the $K - \tau$ model yields $K \sim y^2$ for the entire interval $0 < y^+ < 10$; it yields the proportionality constant $\alpha^+ \doteq 0.05$ – a result that is well within the range of the experimental data.

In Figure 6, the profile of the turbulent dissipation rate predicted by the $K - \tau$, $K - \omega$ and $K - \epsilon$ models are compared. Although the results are fairly close for $y^+ > 20$, there are some significant differences close to the wall. The $K - \tau$ model yields a value for the turbulent dissipation rate at the wall of $\epsilon_w^+ \doteq 0.1$ which is quite close to the value obtained from experiments [2]. Likewise, the peak in ϵ^+ is quite close to the value obtained from experiments [2]. In contrast to these results, the $K - \omega$ model and $K - \epsilon$ model of Launder and Sharma yield values for the wall dissipation ϵ_w^+ that are substantially too small. In Figure 7, the variation of f_μ with y^+ is shown for these three models. Only the $K - \tau$ model is within the range of the experimental data compiled by Patel, Rodi, and Scheuerer [2].

We did not compare directly with the results of the $K - \epsilon$ model of Chien [7] since Chien's model was calibrated by (and, hence, forced into agreement with) the experimental data for the flat plate turbulent boundary layer at zero pressure gradient. However, the fact that this model has some inconsistencies can be seen in the results for f_μ . In Figure 8, a comparison of the predictions of the $K - \tau$ model and the $K - \epsilon$ model of Chien [7] for f_μ is shown. It is clear from this figure that the model of Chien yields values for f_μ that are far removed from the experimental data. Furthermore, the $K - \epsilon$ model of Chien [7] has more ad hoc empiricisms than the $K - \tau$ model presented herein.

The skin friction predicted by the $K - \tau$ model is shown as a function of the coordinate x along the plate in Figure 9. It is clear that the results are in excellent agreement with the experimental data [17]. In Table 1, the fully-developed skin friction and wall dissipation rate are tabulated for the four models considered in this study. Only the $K - \tau$ model and $K - \epsilon$ model of Chien yield results that are within the range of the experimental data. However, it must be remembered that the Chien model was calibrated by forcing it into agreement with the experimental data for this flow.

The more desirable features of τ as a variable instead of ϵ can be seen by a comparison of Figure 10 with Figure 6. It is clear from Figure 10 that the turbulent time scale varies much more smoothly with the distance from the wall; its first derivative with respect to y does not change sign.

5. CONCLUSIONS

A basic theoretical and computational study of two-equation models for near wall turbulent flows has been conducted. The major findings of this study can be summarized as follows:

- (1) The $K - \omega$ model of Wilcox and co-workers [3, 4] is missing an exact viscous cross diffusion term. Furthermore, the destruction of dissipation term is not properly damped near a wall. These two inconsistencies give rise to asymptotically incorrect solutions for the turbulent kinetic energy ($K \sim y^{3.23}$) near a solid boundary.
- (2) The $K - \varepsilon$ model can be made asymptotically consistent by the satisfaction of two constraints: the coefficient of the destruction of dissipation term must be damped of $\mathcal{O}(y^2)$ near a wall, and the coefficient in the eddy viscosity must be damped of $\mathcal{O}(1/y)$ near a wall. Most existing corrections to the $K - \varepsilon$ model yield poor results in near wall turbulent flows due to the violation of these constraints.
- (3) There are numerical stiffness problems with the $K - \varepsilon$ model due to the lack of natural boundary conditions for the dissipation rate and the fact that the balance of terms for the dissipation at the wall involves unknown higher-order correlations which need to be modeled. These problems can, to a large extent, be overcome by the use of the turbulent time scale $\tau \equiv K/\varepsilon$ as a variable since τ has natural boundary conditions arising from the no-slip condition and since the wall balance for τ only involves exact viscous terms.
- (4) A new $K - \tau$ model was developed by making use of these ideas combined with a variation of wall damping functions for f_2 and f_μ that were recently developed by Myong and Kasagi [13]. A preliminary test of this $K - \tau$ model for the turbulent flat plate boundary layer yielded results that are quite encouraging. However, further tests and possible refinements are required before more definitive conclusions can be drawn.

Future research will be directed on two fronts. The $K - \tau$ model will be subjected to more stringent tests involving adverse pressure gradients (with possible flow separation) and high speed compressible flows. The turbulent Prandtl numbers σ_{τ_1} and σ_{τ_2} will be optimized over a range of such flows. In addition, the modeled τ -transport equation will be used in conjunction with a nonlinear algebraic stress model as well as a second-order closure model. One of the major goals in undertaking this research was to ultimately develop second-order closure models that can be integrated directly to a solid boundary in complex turbulent flows that involve separation. These more complex issues will be the subject of our ongoing research effort on turbulence modeling.

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Model	ε_w	C_f
$K - \tau$	0.094	0.00245
$K - \varepsilon$ Launder-Sharma	0.021	0.00238
$K - \varepsilon$ Chien	0.113	0.00244
$K - \omega$	0	0.00244
Experiments [2, 17]	0.05 - 0.10	0.00243

Table 1. Comparison of the model predictions for the wall dissipation rate ε_w and skin friction C_f ($x = 4.987m$, $R_\theta = 16,465$, and $Re_x = 1.156 \times 10^7$).

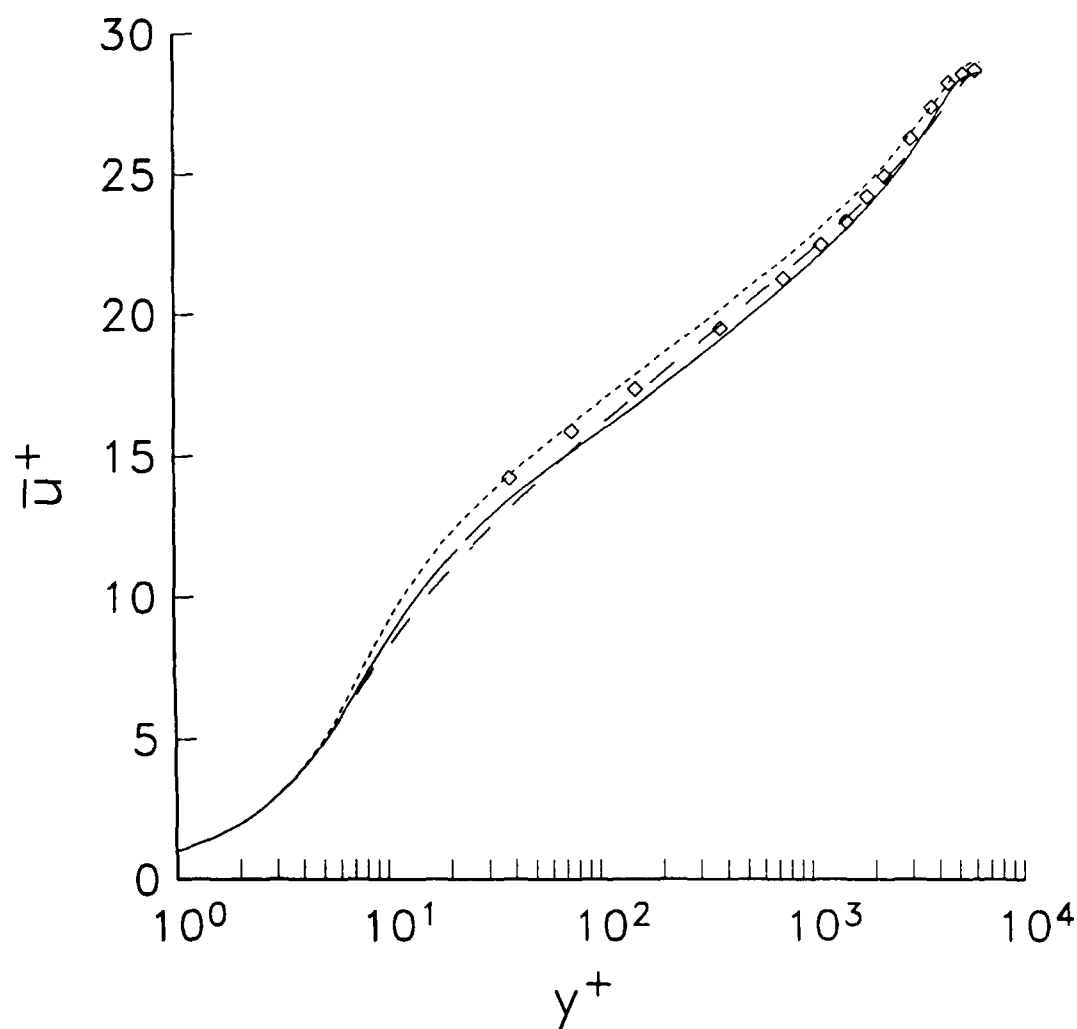


Figure 1. Mean velocity profile predictions for the flat plate turbulent boundary layer ($Re_\theta \approx 16,000$): — $K - \tau$ model; - - - $K - \omega$ model; \cdots $K - \epsilon$ model of Launder and Sharma [6]; \diamond experimental data [2].

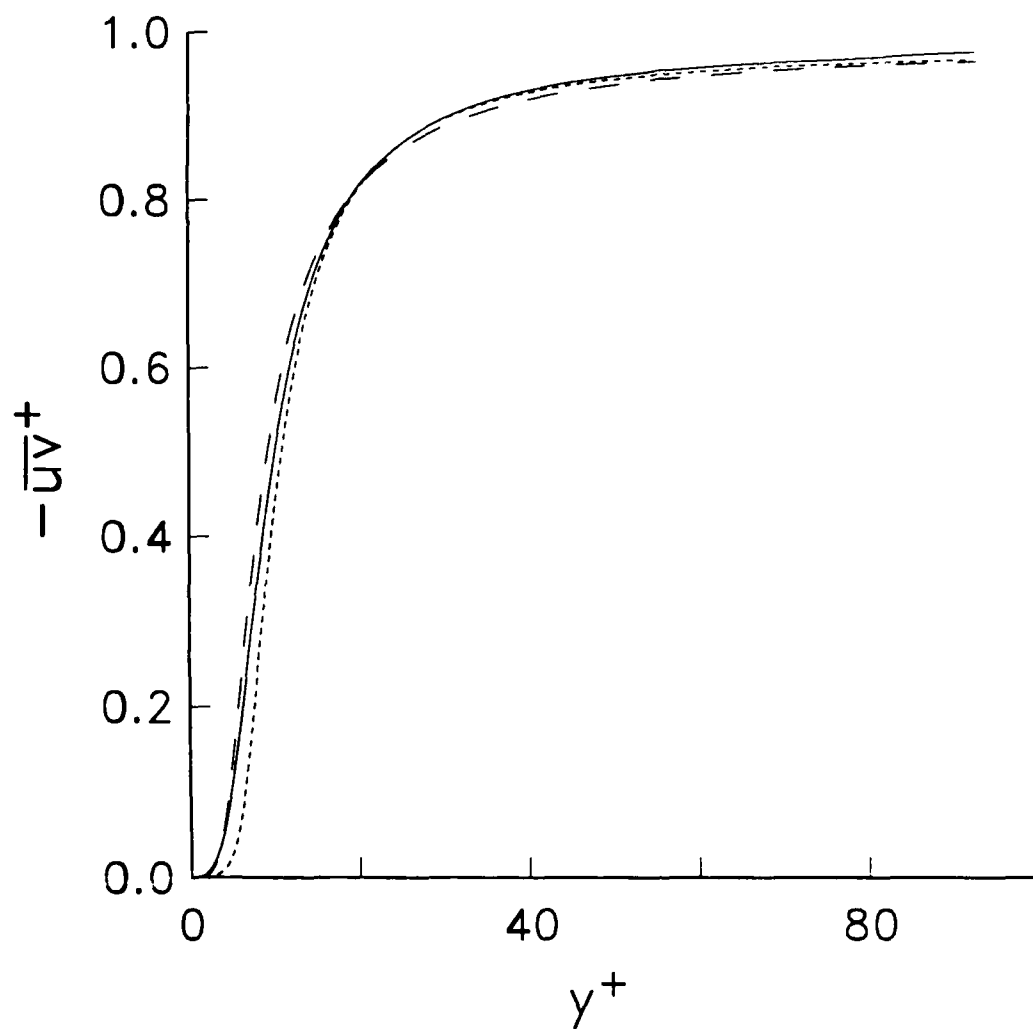


Figure 2. Reynolds shear stress profiles (legend the same as in Figure 1).

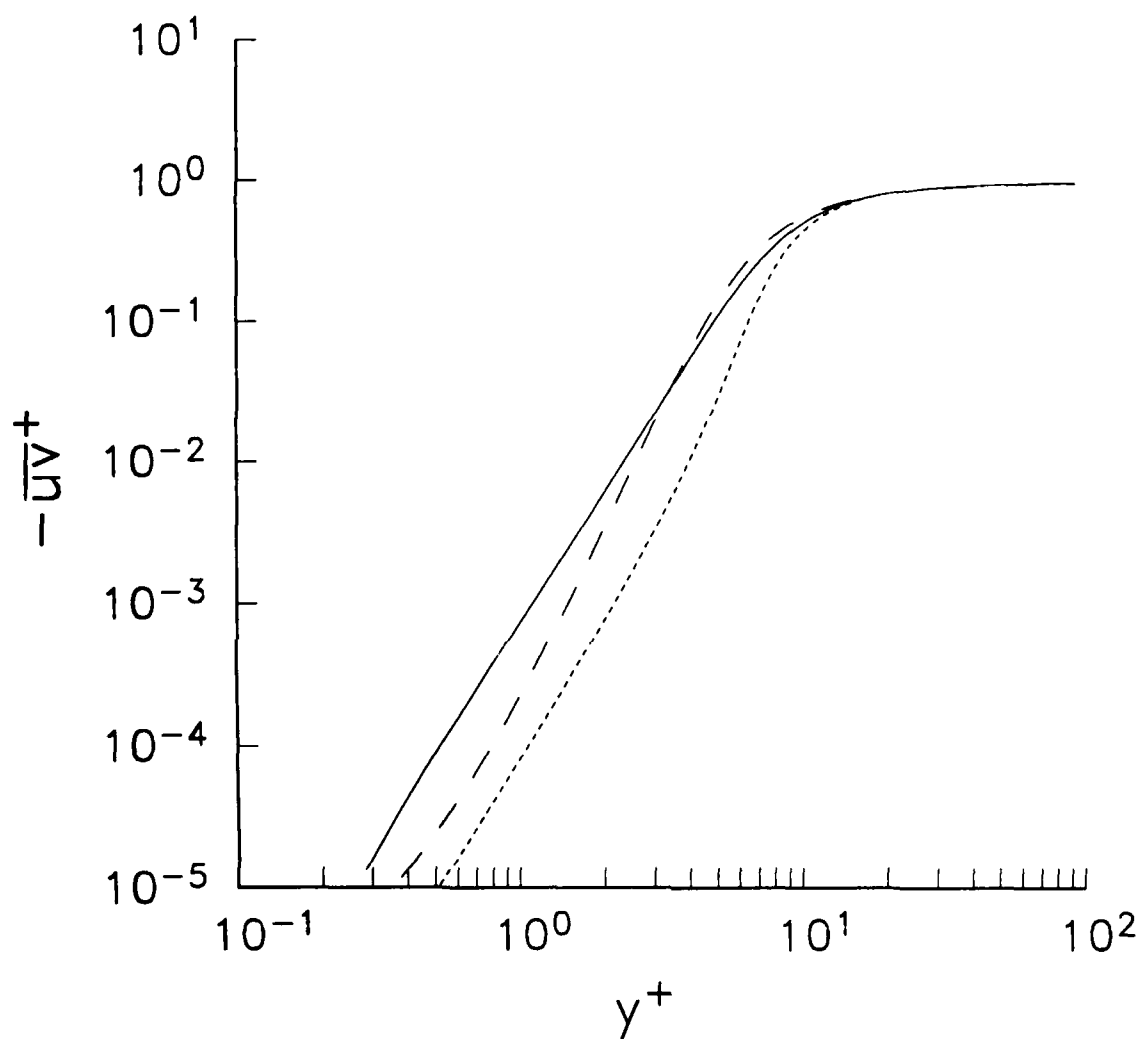


Figure 3. Reynolds shear stress profiles in logarithmic coordinates (legend the same as in Figure 1).

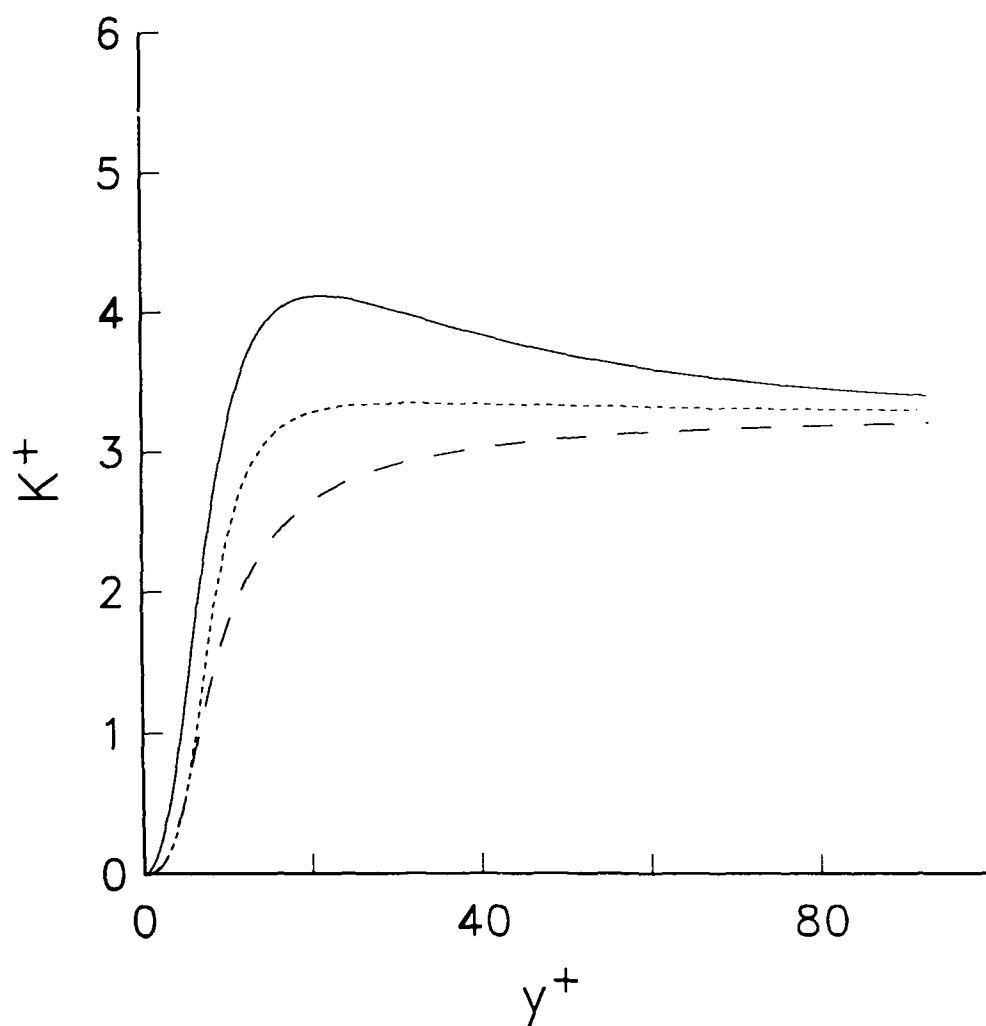


Figure 4. Turbulent kinetic energy profiles (legend the same as in Figure 1).

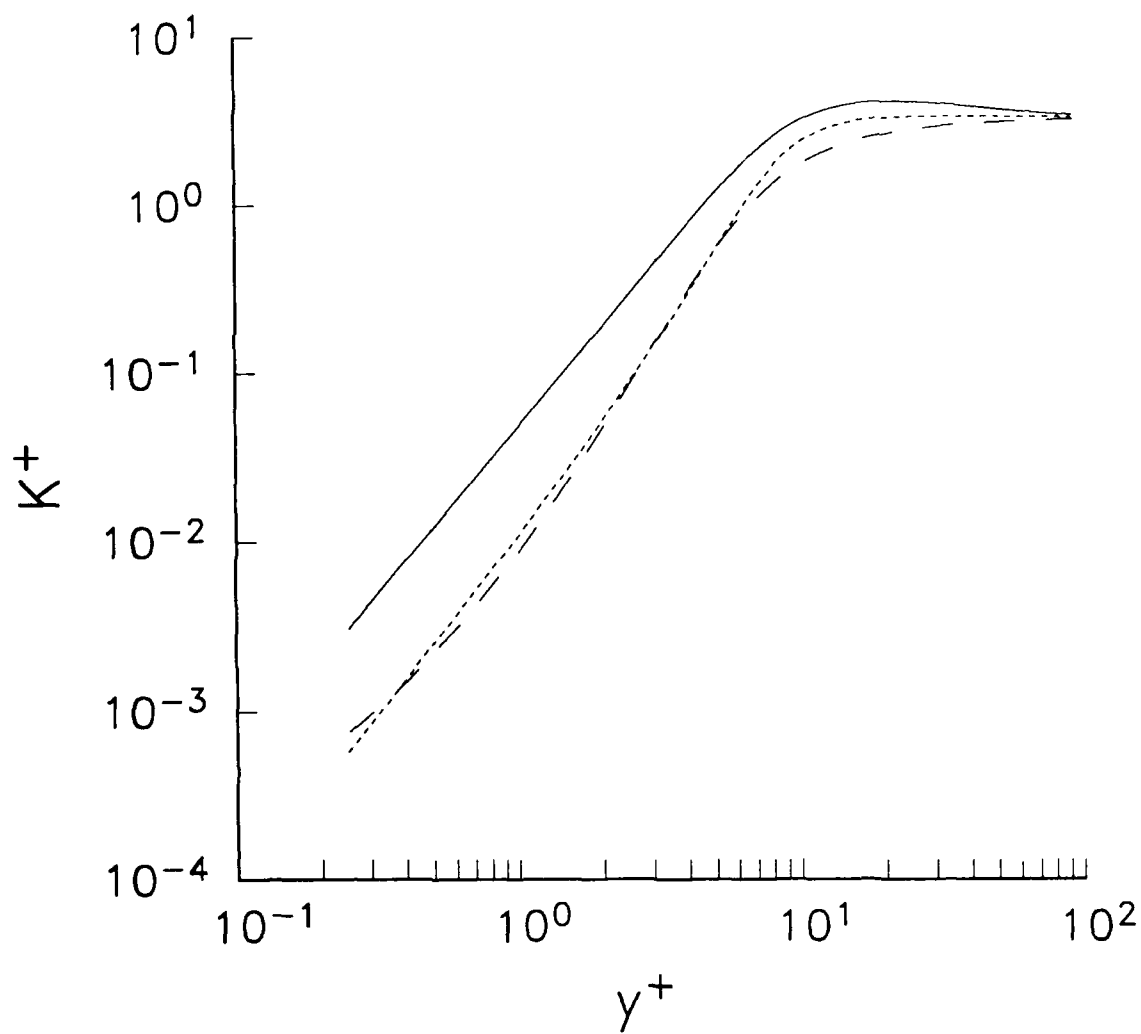


Figure 5. Turbulent kinetic energy profiles in logarithmic coordinates (legend the same as in Figure 1).

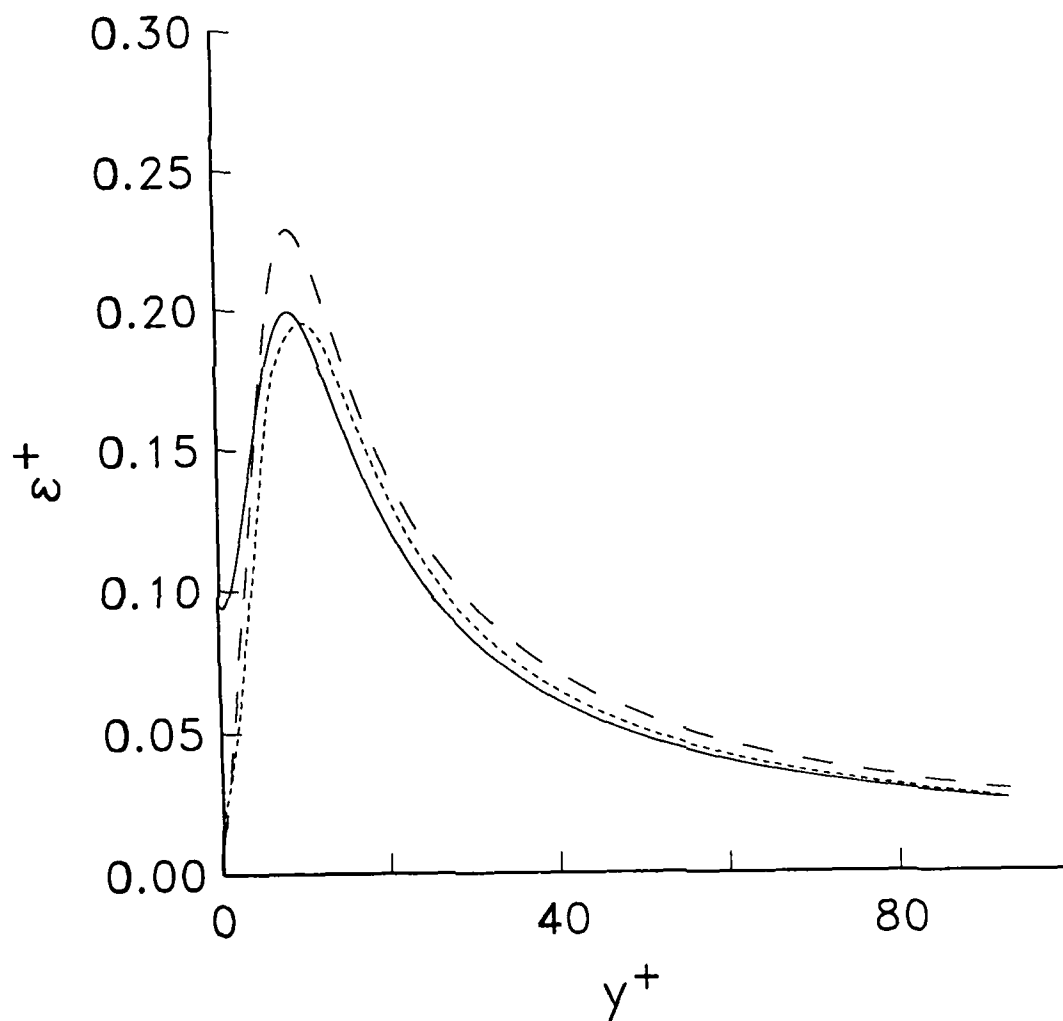


Figure 6. Turbulent dissipation rate profiles (legend the same as in Figure 1).

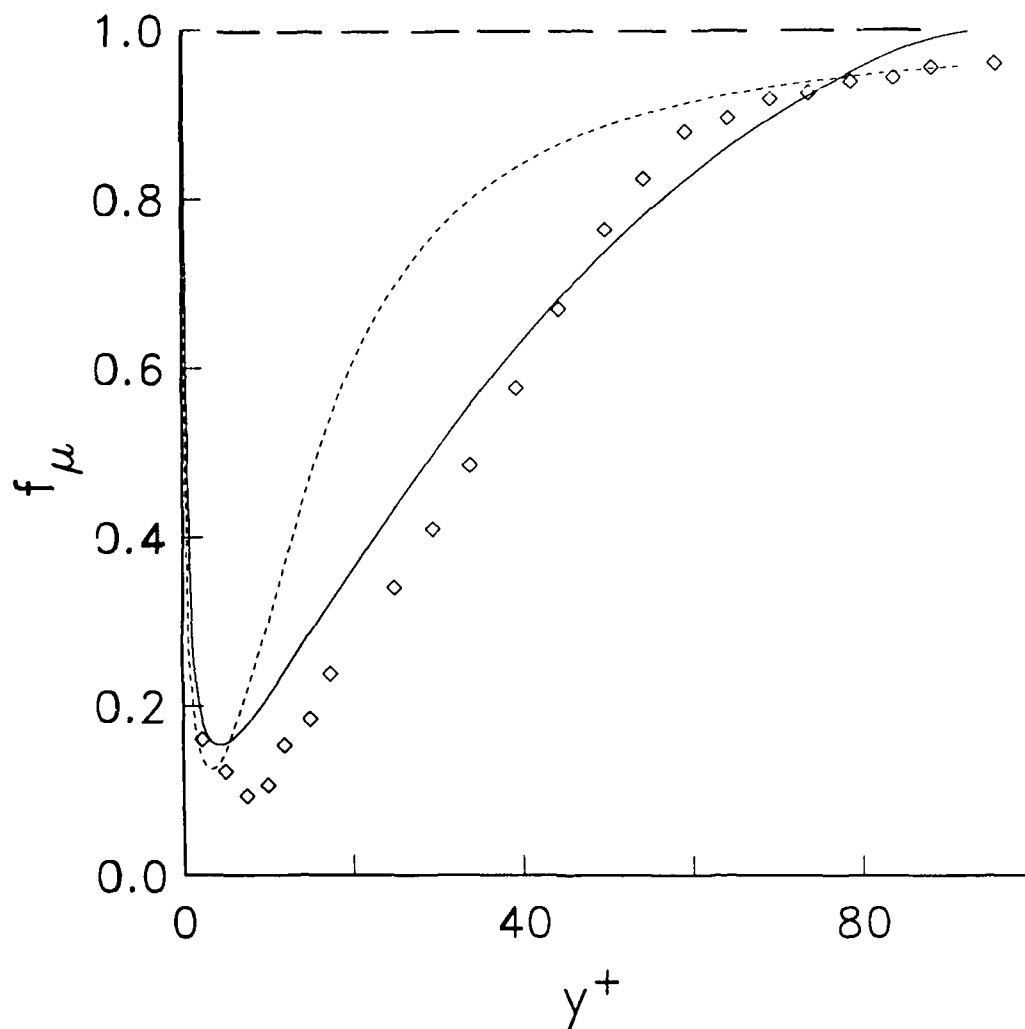


Figure 7. Profiles of the damping function f_μ (legend the same as in Figure 1).

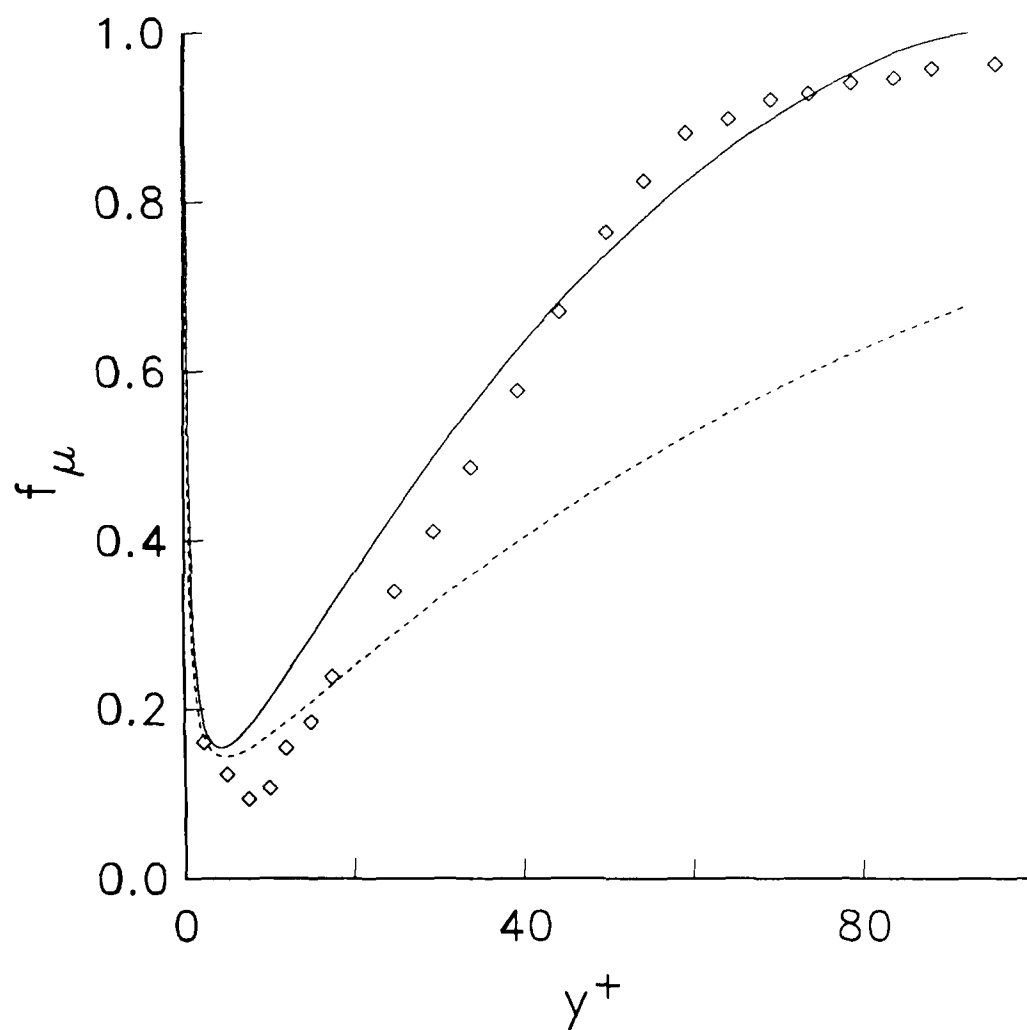


Figure 8. Comparison of the predictions of the $K - \tau$ model (—) and the Chien [7] $K - \epsilon$ model (···) for the wall damping function f_μ (\diamond experimental data [2]).

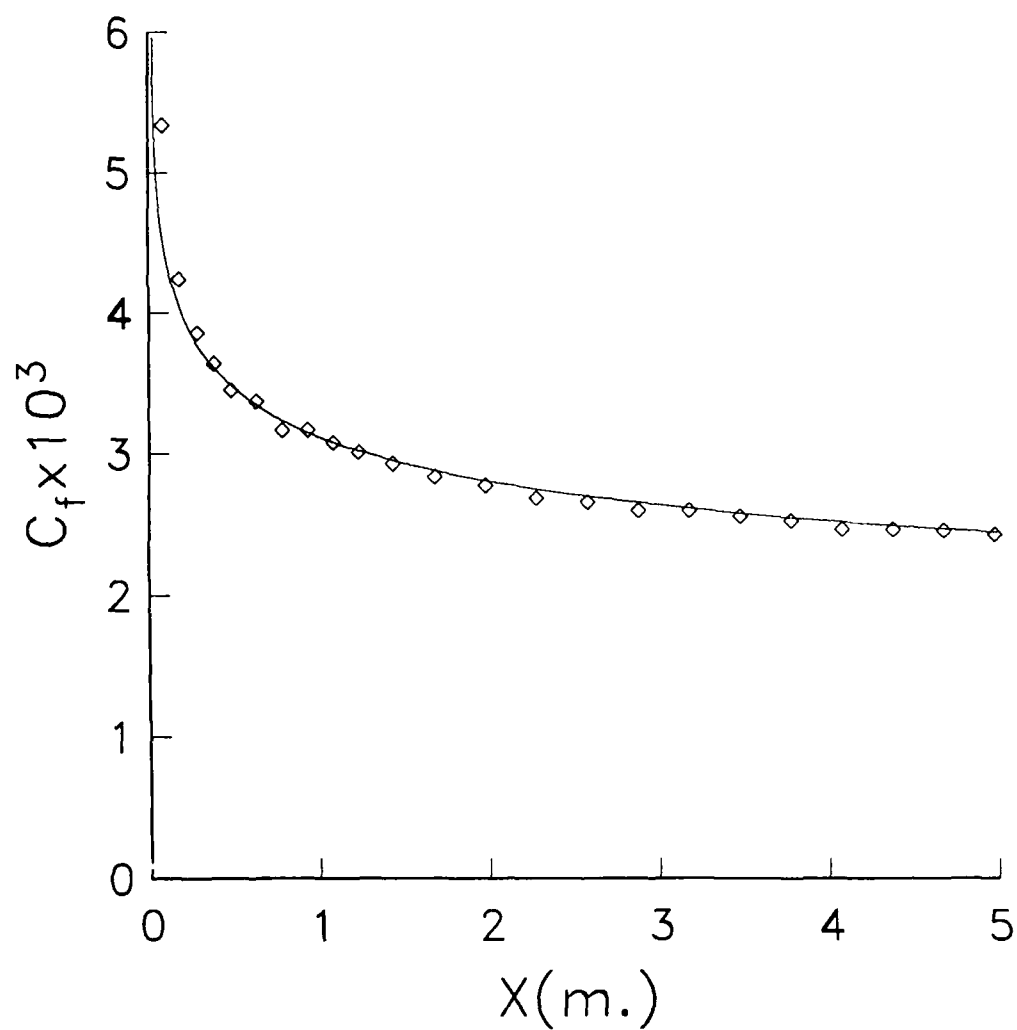


Figure 9. Comparison of the predictions of the $K - \tau$ model for the skin friction with experimental data [17].

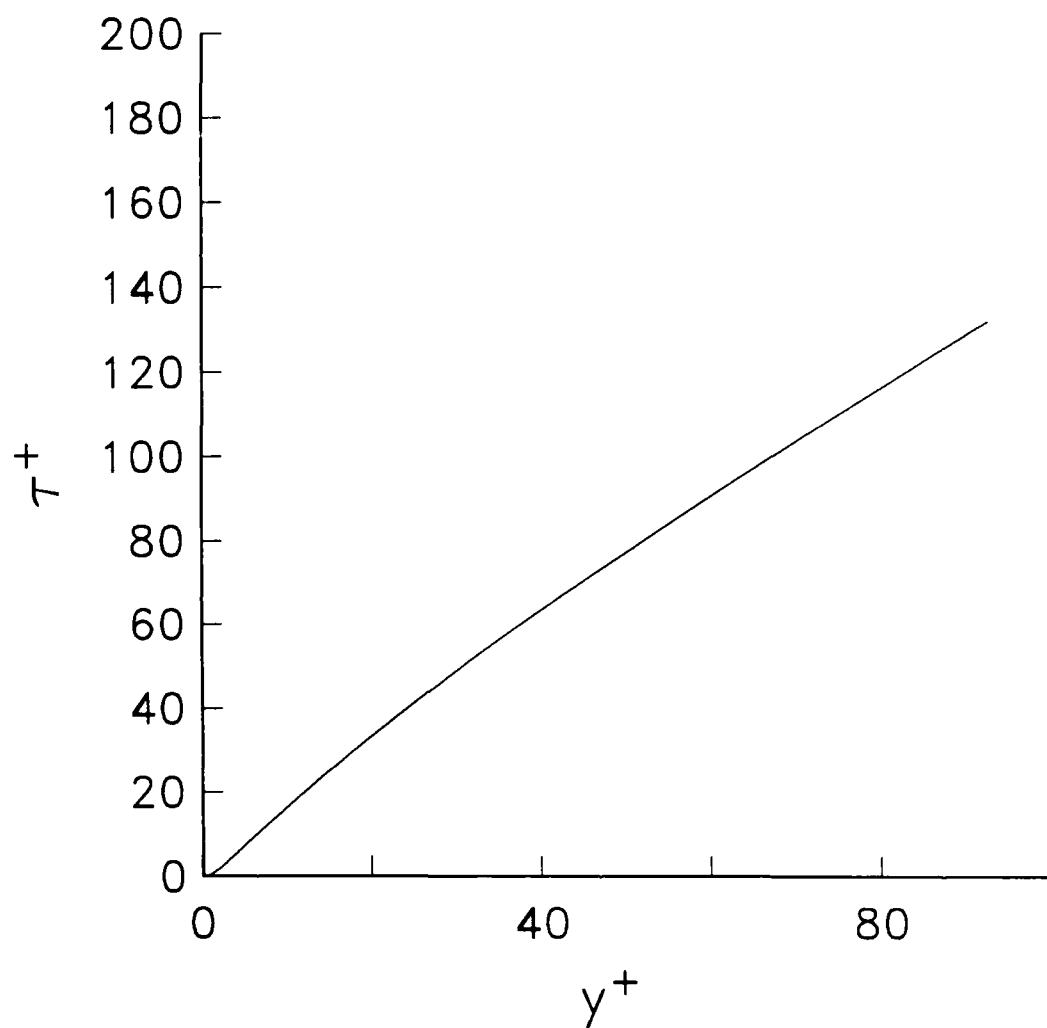


Figure 10. Prediction of the $K - \tau$ model for the turbulent time scale profile ($Re_\theta \approx 16,000$).

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16. Abstract A variety of two-equation turbulence models - including several versions of the K- ϵ model as well as the K- ω model - are analyzed critically for near wall turbulent flows from a theoretical and computational standpoint. It is shown that the K- ϵ model has two major problems associated with it: the lack of natural boundary conditions for the dissipation rate and the appearance of higher-order correlations in the balance of terms for the dissipation rate at the wall. In so far as the former problem is concerned, either physically inconsistent boundary conditions have been used or the boundary conditions for the dissipation rate have been tied to higher-order derivatives of the turbulent kinetic energy which leads to numerical stiffness. The K- ω model can alleviate these problems since the asymptotic behavior of ω is known in more detail and since its near wall balance involves only exact viscous terms. However, the modeled form of the ω equation that is used in the literature is incomplete - an exact viscous term is missing which causes the model to behave in an asymptotically inconsistent manner. By including this viscous term - and by introducing new wall damping functions with improved asymptotic behavior - a new K- τ model (where $\tau \equiv 1/\omega$ is turbulent time scale) is developed. It is demonstrated that this new model is computationally robust and yields improved predictions for turbulent boundary layers.					
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